Long Lived Particles Searches in Heavy Ion Collisions at the LHC

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STEALTH physics at LHCb: unleashing the full power of LHCb to probe new physics

Low scale seesaw (type I)

[Minkowski 1977; Mohapatra et al. 1980]

Three right handed neutrinos

$$\mathcal{L}_{\nu_R} = -y_{ai}\bar{\ell}_a \varepsilon \phi \nu_{Ri} - \frac{1}{2}\overline{\nu^c_{R}}_i M_{ij} \nu_{Rj} + \text{h.c.}$$

y_{ai} Yukawa coupling $\quad$ M_{ij} Majorana mass

Electroweak symmetry breaking

Dirac mass $m_{ai} = v y_{ai}$

Seesaw mechanism

$$m_\nu = -m_{ai} M^{-1}_{ij} m^T_{bj} = -\theta_{ai} M_{ij} \theta^T_{bj} \ , \qquad \theta_{ai} = m_{aj} M^{-1}_{ij}$$

produces tiny masses for the left handed neutrinos

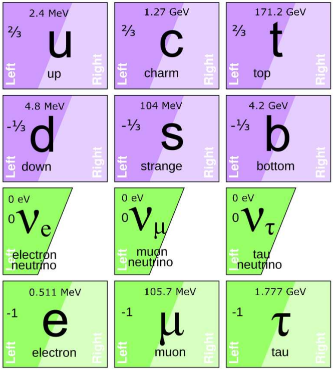
Small mixing into mass eigenstates

$$\nu \simeq U^\dagger_\nu \left(\nu_L - \theta \nu^c_R\right) \ , \qquad N \simeq \nu_R + \theta^T \nu^c_L$$

Coupling of N_i to the SM

$$\mathcal{L} \supset -\frac{m_W}{v} \overline{N} \theta^*_a \gamma^\mu e_{La} W^+_\mu - \frac{m_Z}{\sqrt{2}v} \overline{N} \theta^*_a \gamma^\mu \nu_{La} Z_\mu - \frac{M}{v} \theta_a h \overline{\nu_{L\alpha}} N + \text{h.c.}$$

Complements SM fields



νMSM may explain

- Neutrino oscillation
- Neutrino masses
- Leptogenesis
- Dark matter

Abbreviation

$$U^2_a = \sum_i U^2_{ai} \ , \quad U^2_{ai} = |\theta_{ai}|^2$$

νMSM

[Asaka et al. 2005; Shaposhnikov 2007]

SM is symmetric under $B-L$

Majorana mass M_{ij} breaks this symmetry

The $B-L$ symmetry is restored

- in the limit of $M_{ij} \to 0$
- if ν_{Ri} form pseudo Dirac pairs $\nu_{Ri} + \nu_{Rj}^c$

$B-L$ violating parameter

ϵ, ϵ', μ, μ' are small

Mass matrix

$$M_{ij} = M \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

- Almost mass degenerate pseudo dirac pair
- lighter $\mathcal{O}(\text{keV})$ dark matter candidate

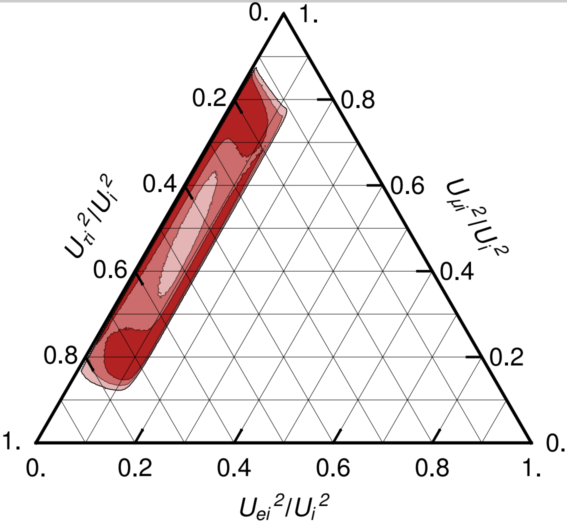
Yukawa coupling

$$y_{ai} = \begin{pmatrix} y_e + \epsilon_e & \mathrm{i}(y_e - \epsilon_e) & \epsilon'_e \\ y_\mu + \epsilon_\mu & \mathrm{i}(y_\mu - \epsilon_\mu) & \epsilon'_\mu \\ y_\tau + \epsilon_\tau & \mathrm{i}(y_\tau - \epsilon_\tau) & \epsilon'_\tau \end{pmatrix}$$

- pseudo Dirac pair with coupling $\mathcal{O}(y)$
- Dark matter candidate with coupling $\mathcal{O}(\epsilon')$

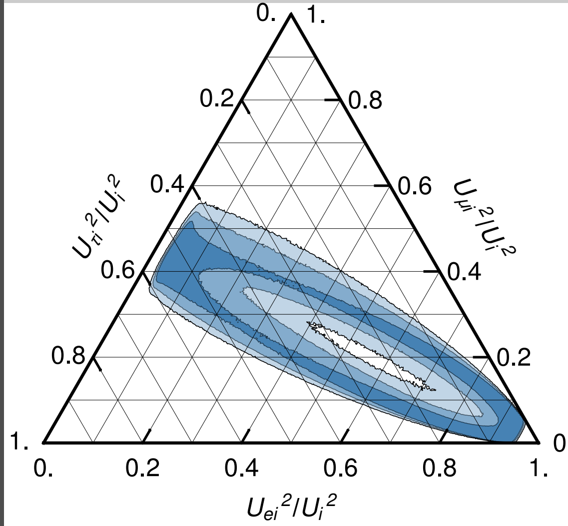
Probability contours for U_{ai}^2 (two active flavours)

Normal Ordering



Flat prior on α

Inverted Ordering



Flat prior on α

Coloured areas consistent

with neutrino oscillation data at 1, 2, and 3 σ

Unknown Majorana phase α

correspond to the circular structure

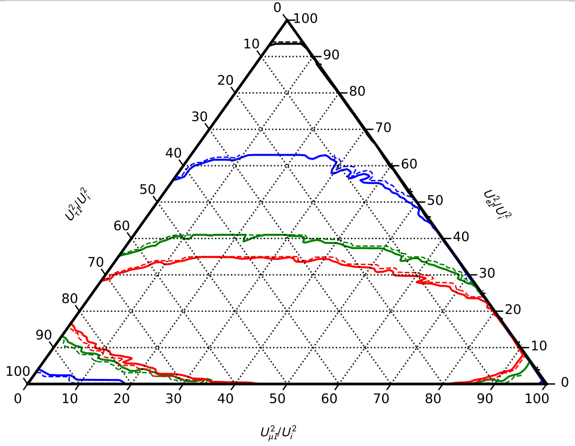
Probability contours are

stable against change of prior on Majorana phase α

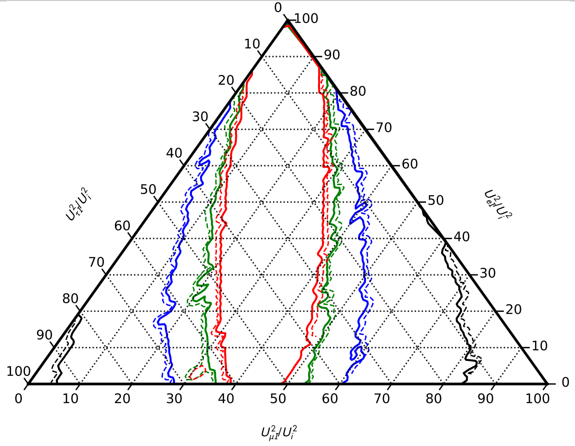
Probability contours for U^2_{ai} (three active flavours)

[Chrzaszcz et al. 2019]

Normal Ordering



Inverted Ordering



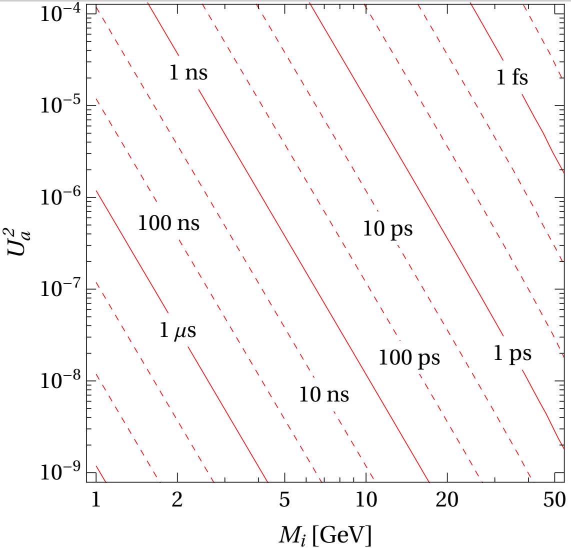
Contours depend on

$m_{\nu_0} < 0.01, 0.1, 1, 10\,\text{meV}$ for 1 and $2\,\sigma$

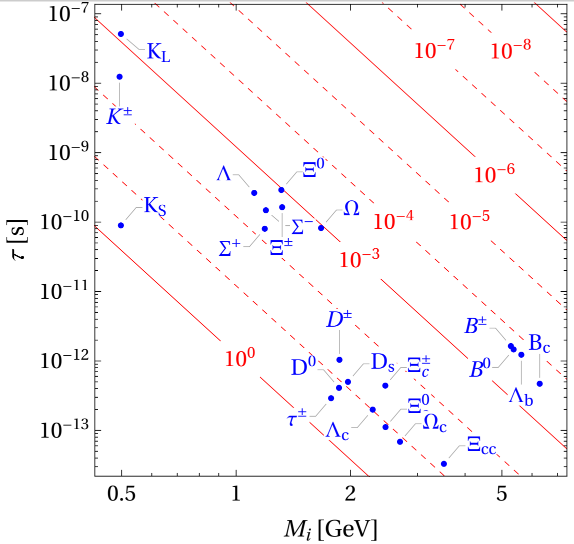
The non-minimal case is considerably less predictive

Properties

Lifetime



SM background vs. coupling strength U^2

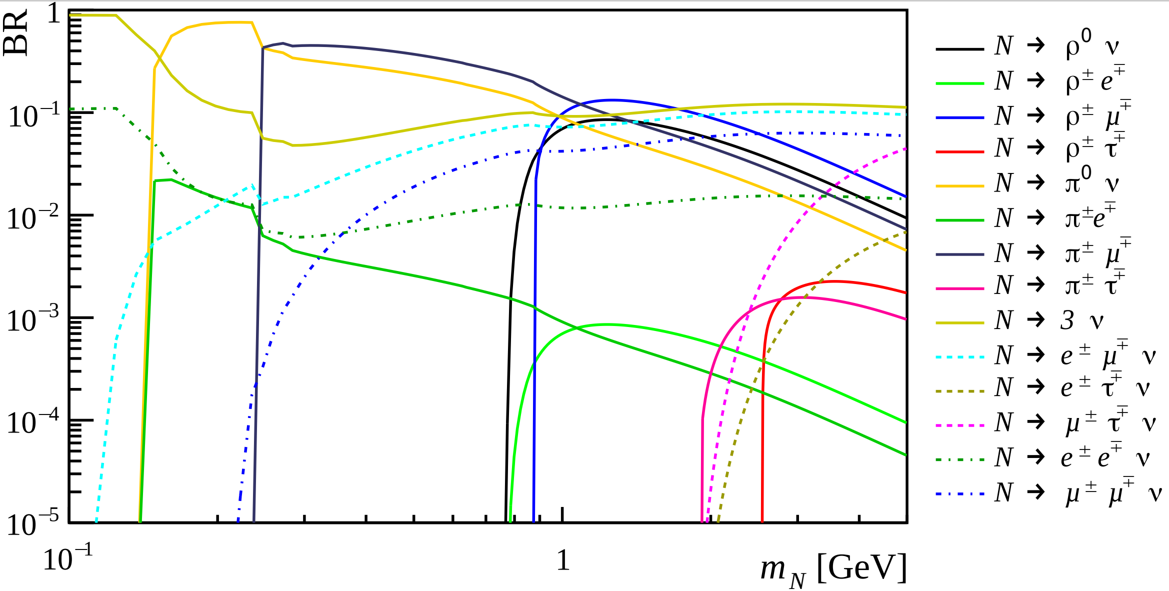


Decay width for $M \gg 5\,\mathrm{GeV}$

$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5 \ ,$$

Branching Fractions

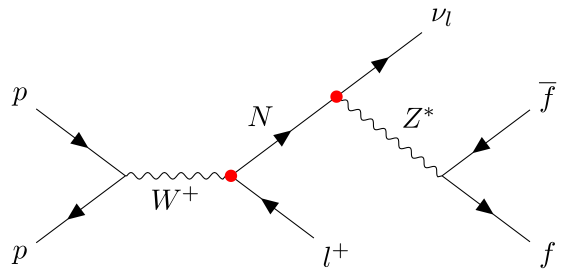
For $U_{ie}^2 : U_{i\mu}^2 : U_{i\tau}^2 = 1 : 160 : 27.8$



Proton Collisions

Signature

Z-decay



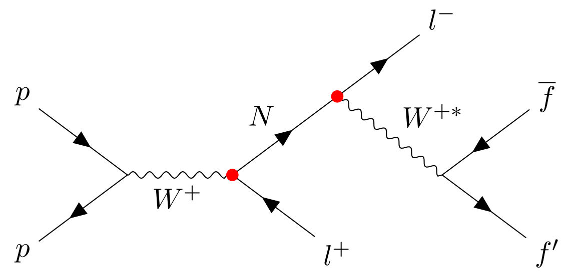
Search strategy

- trigger on first lepton
- search for secondary vertex

Muon chamber [Bobrovskyi et al. 2011; CMS 2015]

- muon chamber reaches farther than tracker
- long lived particles can be search for using only muon chambers

W-decay

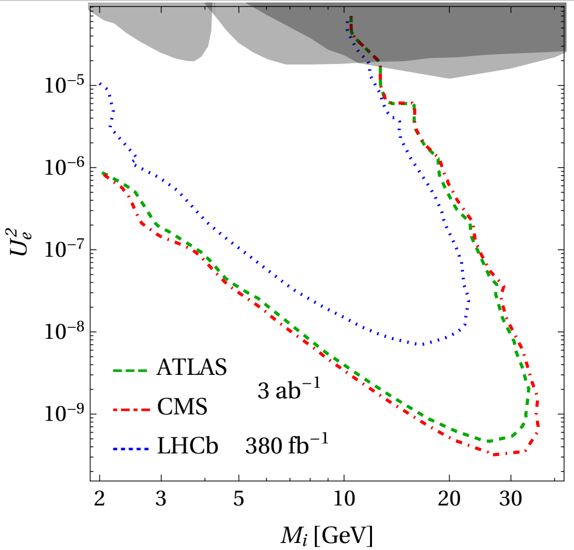


Displaced vertex reconstruction

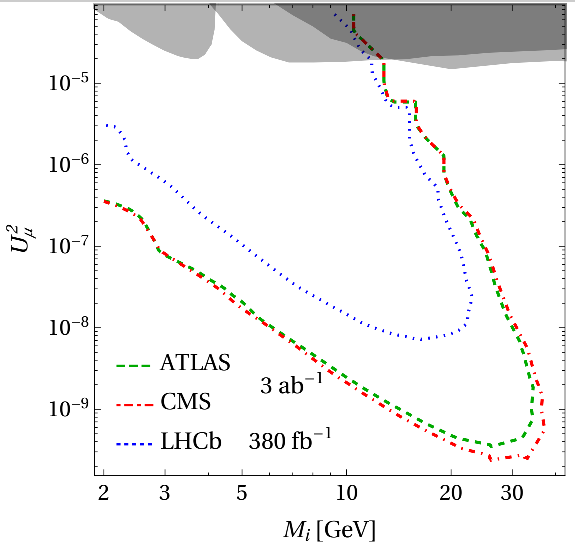
- at least 2 tracks
- particles must transverse at least half of the tracker
- or the complete muon chamber

Maximal exclusion reach

pure U_e^2

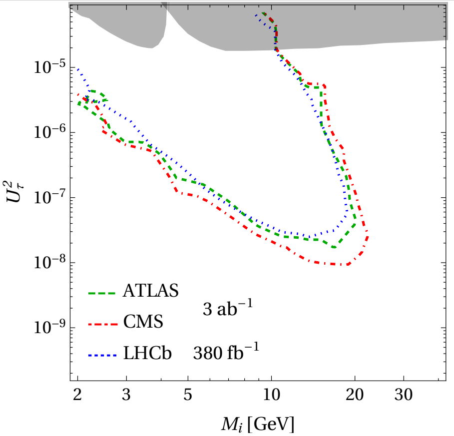


pure U_μ^2



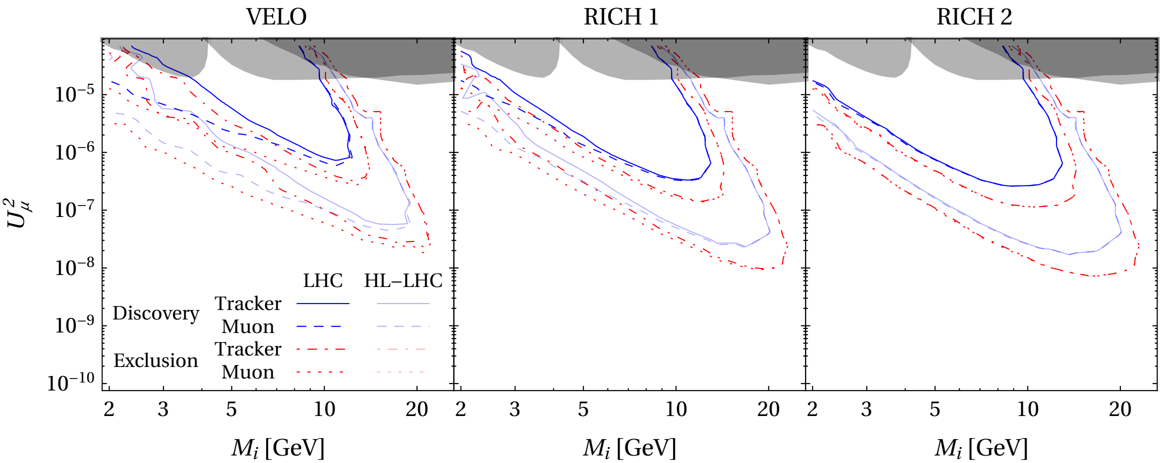
Maximal exclusion reach

pure U_τ^2



p_T^{min} of ATLAS single lepton and lepton pair triggers [ATLAS 2017]

	Single Lepton			Lepton Pair					
	e	μ	τ	e, e	e, μ	e, τ	μ, μ	μ, τ	τ, τ
p_T^{min} [GeV]	27	27	170	18, 18	8, 25 18, 15	30, 18	15, 15 23, 9	30, 15	40, 30


VELO
RICH 1
RICH 2
U_μ^2
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
2
3
5
10
20
M_i [GeV]
LHC
HL–LHC
Discovery
Tracker
Muon
Exclusion
Tracker
Muon

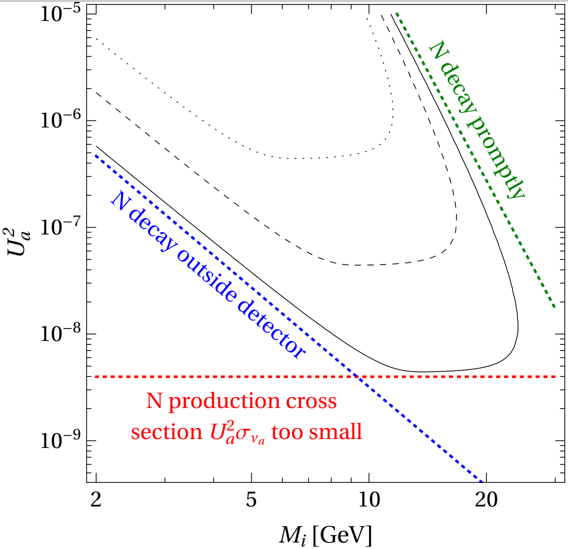
Expectations

Simplified model

$$N_d \sim L_{\text{int}} \sigma_\nu U^2 \left(e^{-l_0/\lambda_N} - e^{-l_1/\lambda_N} \right) f_{\text{cut}} \ ,$$

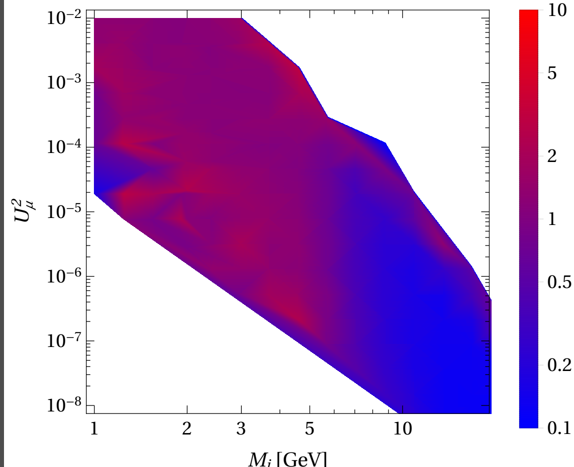
l_0 minimal displacement l_1 detector length $\lambda_N = \frac{\beta\gamma}{\Gamma_N}$ decay length

Significances and major obstacles



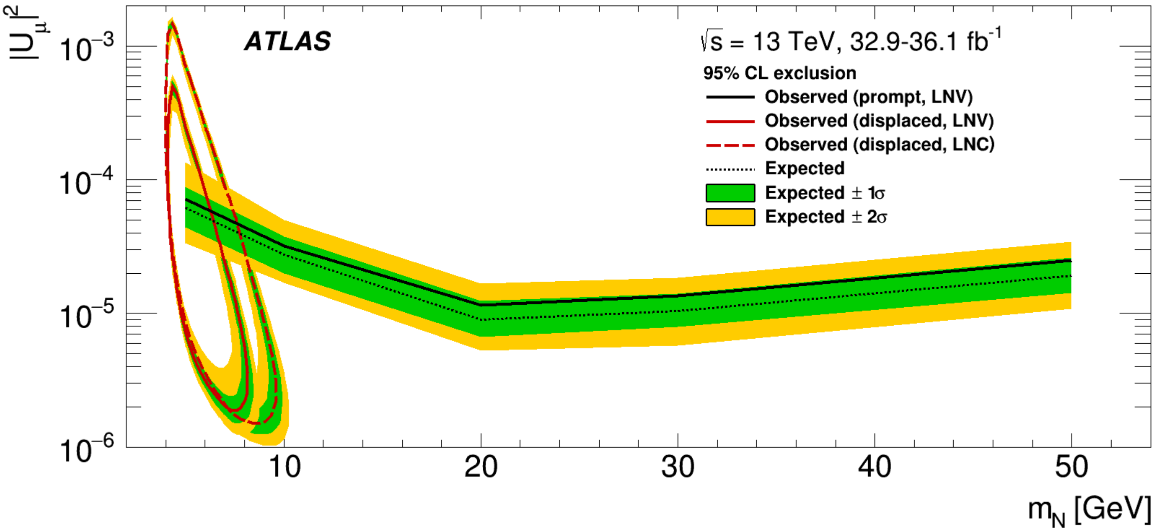
Deviation

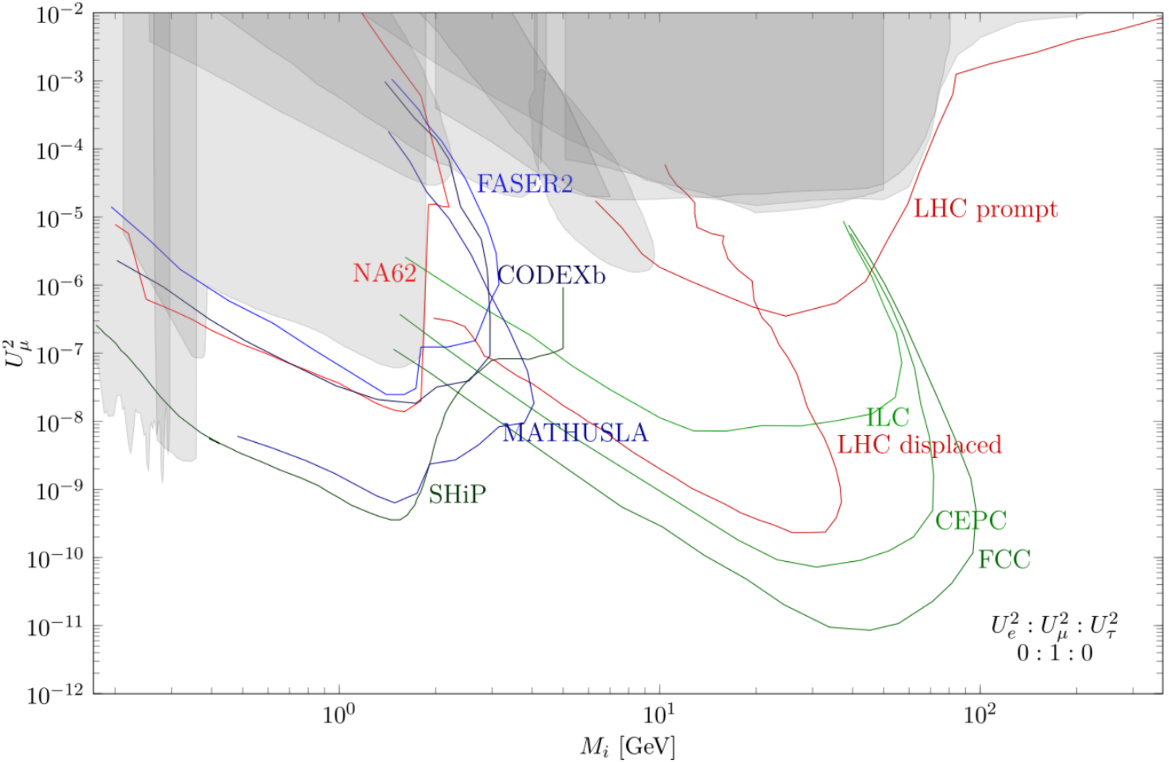
of simplified model from full simulation



Prompt and displaced results for U_μ^2

[ATLAS 2019]





10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
U_μ^2
10^0
10^1
10^2
M_i [GeV]
FASER2
LHC prompt
NA62
CODEXb
ILC
MATHUSLA
LHC displaced
SHiP
CEPC
FCC
$U_e^2 : U_\mu^2 : U_\tau^2$
0 : 1 : 0

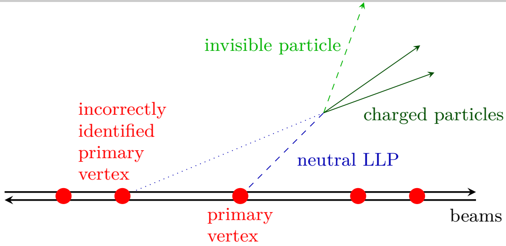
Heavy Ion Collisions

Properties of the heavy ions runs

Advantage

- No pile-up; single primary vertex
- Large nucleon multiplicity
  e.g. $A(\text{Pb}) = 208$, $Z(\text{Pb}) = 82$
- Number of parton level interactions per collision scales with A
  e.g. $\frac{\sigma_{\text{PbPb}}}{\sigma_{pp}} \propto A^2 = 43 \times 10^3$

Single primary vertex



Better event reconstruction possible

Drawbacks

- There are a huge number of tracks near the interaction point which makes the search for prompt new physics extremely challenging
- The collision energy per nucleon is smaller. e.g. $\sqrt{s_{NN}} = 5.02\,TeV$ for Pb which is problematic for heavy new physics
- The instantaneous luminosity is lower for heavier ions
- The LHC has allocated much less time to heavy ions runs than to protons runs

Possible ways out

- Low luminosity allows for lower triggers
- Lighter ions allow for higher luminosity

The reason for the low luminosities are secondary beams [Jowett 2018]

For heavy ions there are additional contributions to the crosssection

[Meier et al. 2001]

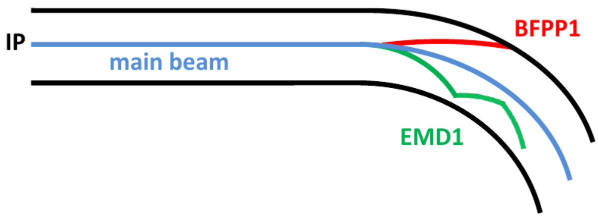
Bound-Free Pair Production (BFPP): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+}$

[Pshenichnov et al. 2001]

Electromagnetic Dissociation (EMD): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n$

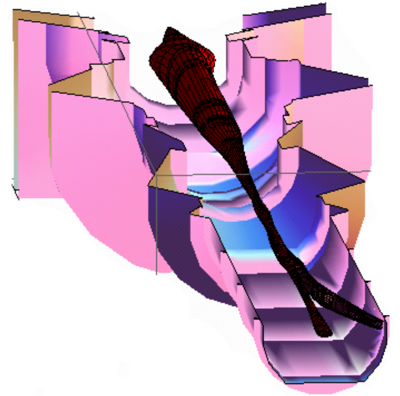
Leads to [Schaumann 2015]

- Larger cross section results in faster beam decay
- Secondary beams consisting of ions with different charge/mass ratio



Can accidentally quench the magnets

[Bruce et al. 2018]



Luminosity

[Benedikt et al. 2015]

The luminosity at one interaction point (IP) is

$L \propto N_b^2$ where N_b are number of ions per bunch

The initial bunch intensity [Jowett 2018]

for arbitrary ions is fitted to the information of the lead run

$$N_b\left({}^{A}_{Z}\mathrm{N}\right) = N_b\left({}^{208}_{82}\mathrm{Pb}\right)\left(\frac{Z}{82}\right)^{-p}$$

where $p = 1$ is a conservative assumption while $p = 1.9$ is a optimistic assumption.

The loss of number of ions per bunch N_b over time is given by

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0\tau_b}\,, \qquad \tau_b = \frac{n_b}{\sigma_{\mathrm{tot}} n_{\mathrm{IP}}}\frac{N_0}{L_0}\,,$$

where n_{IP} is the number of interaction points.

For a given turnaround time t_{ta} between the physics runs

the integrated luminosity is maximised by

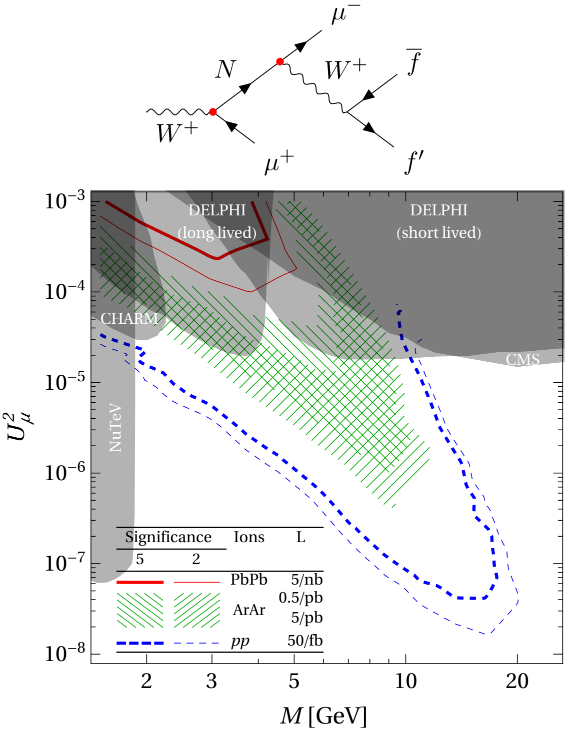
$$t_{\mathrm{opt}} = \tau_b\sqrt{\theta_{\mathrm{ta}}}\,, \qquad \text{with} \qquad \theta_{\mathrm{ta}} = \frac{t_{\mathrm{ta}}}{\tau_b}\,.$$

The average luminosity using the optimal run time is

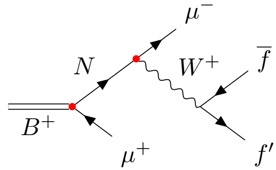
$$L_{\mathrm{ave}}(t_{\mathrm{opt}}) = \frac{L_0}{\left(1+\sqrt{\theta_{\mathrm{ta}}}\right)^2}\,.$$

Heavy ion collisions

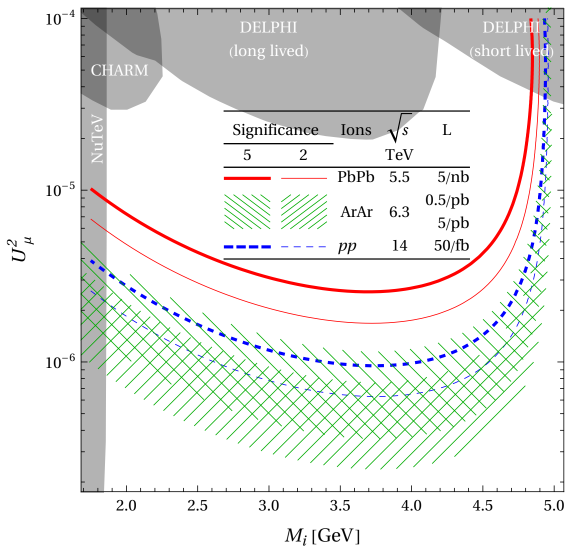
Full simulation of W production



Simplified simulation of B production



Considerable lower trigger of $p_T > 3\,\text{GeV}$ for heavy ion collisions



Conclusion

- Heavy neutrinos constitute a minimal extension to the SM featuring long lived particles
- Displaced vertices are a promising signature to detect right-handed neutrinos at the LHC
- Heavy ion collisions provide a new environment to search for long lived particles

References I

M. Drewes, J. Hajer, J. Klaric, and G. Lanfranchi. "NA62 sensitivity to heavy neutral leptons in the low scale seesaw model". *JHEP* 07, p. 105. DOI: 10.1007/JHEP07(2018)105. arXiv: 1801.04207 [hep-ph].

M. Drewes, A. Giammanco, J. Hajer, M. Lucente, and O. Mattelaer. "A Heavy Metal Path to New Physics". *PRL*. arXiv: 1810.09400 [hep-ph]. №: CP3-18-60.

M. Drewes and J. Hajer. "Heavy Neutrinos in displaced vertex searches at the LHC and HL-LHC". *JHEP* 02, p. 070. DOI: 10.1007/JHEP02(2020)070. arXiv: 1903.06100 [hep-ph]. №: CP3-19-11.

M. Drewes, A. Giammanco, J. Hajer, and M. Lucente. "Long Lived Particles Searches in Heavy Ion Collisions at the LHC". *PRD*. arXiv: 1905.09828 [hep-ph]. №: CP3-19-26.

P. Minkowski. "$\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?" *Phys. Lett.* 67B, pp. 421–428. DOI: 10.1016/0370-2693(77)90435-X. №: Print-77-0182 (BERN).

R. N. Mohapatra and G. Senjanovic. "Neutrino Mass and Spontaneous Parity Violation". *Phys. Rev. Lett.* 44, p. 912. DOI: 10.1103/PhysRevLett.44.912. №: MDDP-TR-80-060, MDDP-PP-80-105, CCNY-HEP-79-10.

T. Asaka and M. Shaposhnikov. "The νMSM, dark matter and baryon asymmetry of the universe". *Phys. Lett.* B620, pp. 17–26. DOI: 10.1016/j.physletb.2005.06.020. arXiv: hep-ph/0505013 [hep-ph].

M. Shaposhnikov. "A Possible symmetry of the νMSM". *Nucl. Phys.* B763, pp. 49–59. DOI: 10.1016/j.nuclphysb.2006.11.003. arXiv: hep-ph/0605047 [hep-ph]. №: CERN-PH-TH-2006-079.

References II

M. Chrzaszcz et al. "A frequentist analysis of three right-handed neutrinos with GAMBIT". arXiv: 1908.02302 [hep-ph].

S. Bobrovskyi, W. Buchmüller, J. Hajer, and J. Schmidt. "Quasi-stable neutralinos at the LHC". *JHEP* 09, p. 119. DOI: 10.1007/JHEP09(2011)119. arXiv: 1107.0926 [hep-ph]. №: DESY-11-077.

CMS. "Search for long-lived particles that decay into final states containing two muons, reconstructed using only the CMS muon chambers". №: CMS-PAS-EXO-14-012.

ATLAS. "Trigger Menu in 2016". ATL-DAQ-PUB-2017-001. URL: https://cds.cern.ch/record/2242069.

ATLAS. "Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector". arXiv: 1905.09787 [hep-ex]. №: CERN-EP-2019-071.

H. Meier, Z. Halabuka, K. Hencken, D. Trautmann, and G. Baur. "Bound free electron positron pair production in relativistic heavy ion collisions". *Phys. Rev.* A63, p. 032713. DOI: 10.1103/PhysRevA.63.032713. arXiv: nucl-th/0008020 [nucl-th].

I. A. Pshenichnov, J. P. Bondorf, I. N. Mishustin, A. Ventura, and S. Masetti. "Mutual heavy ion dissociation in peripheral collisions at ultrarelativistic energies". *Phys. Rev.* C64, p. 024903. DOI: 10.1103/PhysRevC.64.024903. arXiv: nucl-th/0101035 [nucl-th].

M. Schaumann. "Heavy-ion performance of the LHC and future colliders". PhD thesis. Aachen, Germany: RWTH Aachen U. №: CERN-THESIS-2015-195, URN:NBN:DE:HBZ:82-RWTH-2015-050284.

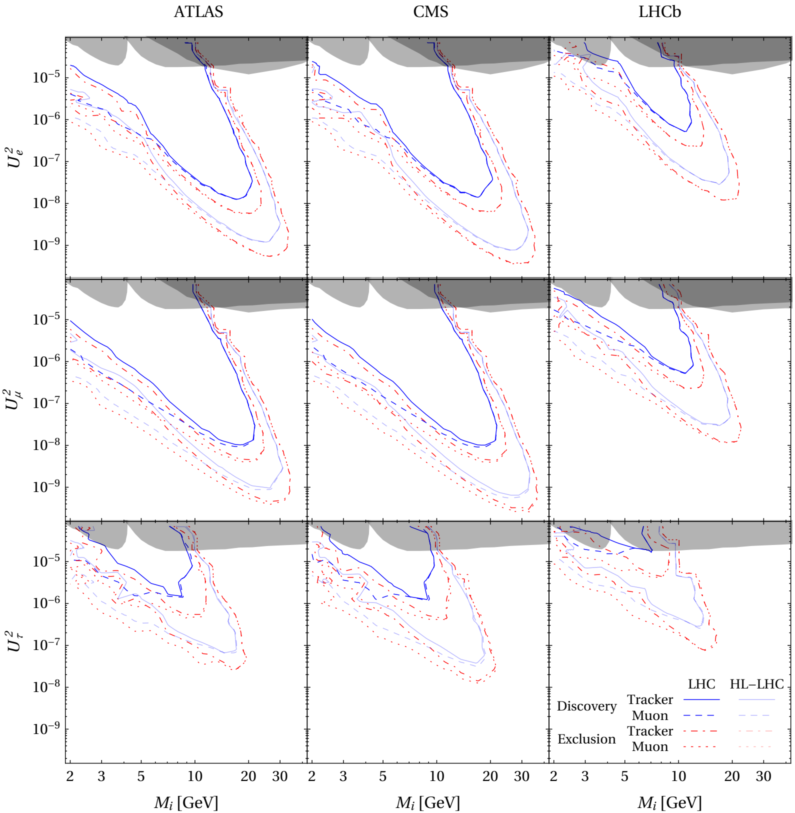
References III

R. Bruce, J. Jowett, and M. Schaumann. "Limitations for heavy-ion performance in the LHC". URL: https://agenda.irmp.ucl.ac.be/event/3186/contributions/3648.

J. Jowett. "HL-LHC performance: Update for HE-LHC and light ions". URL: https://indico.cern.ch/event/686494/timetable.

M. Benedikt, D. Schulte, and F. Zimmermann. "Optimizing integrated luminosity of future hadron colliders". *Phys. Rev. ST Accel. Beams* 18, p. 101002. DOI: 10.1103/PhysRevSTAB.18.101002.

Comparison of the exclusions reaches for the LHC experiments



Comparison for purely leptonic searches